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Hurricane Ivan crossed the Gulf of Mexico as a category 4/5 storm before making landfall in Alabama. Here we show in unprecedented detail the oceanic response generated by Ivan as it crossed the outer continental shelf. The current structure was found to be frictionally dominated with overlapping surface and bottom boundary layers as Ivan approached before transitioning to a dominant surface boundary layer as the wind stress peaked. The strongest currents, largest temperature fluctuations, and greatest transports were generated left of the storm track.

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Observed currents over the outer continental shelf during Hurricane Ivan

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[1] Hurricane Ivan crossed the Gulf of Mexico as a category 4/5 storm before making landfall in Alabama. Here we show in unprecedented detail the oceanic response generated by Ivan as it crossed the outer continental shelf. The current structure was found to be frictionally dominated with overlapping surface and bottom boundary layers as Ivan approached before transitioning to a dominant surface boundary layer as the wind stress peaked. The strongest currents, largest temperature fluctuations, and greatest transports were generated left of the storm track.
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1. Introduction

[2] Hurricane Ivan was one of the most destructive hurricanes to ever enter the Gulf of Mexico. Damage estimates are in the tens of billions of dollars, and do not include offshore damage. Ivan was particularly devastating to the oil industry because it passed through a region hosting a high concentration of the U.S. petroleum infrastructure. According to the U.S. Minerals Management Service (MMS Press Release 3164, October 8, 2004, http://www.mms.gov), 150 platforms and 10,000 miles of pipeline were damaged, five mobile drilling rigs set adrift, and seven sunk entirely. Thus, the oceanic response on the shelf must be fully understood so preparations for future hurricanes will be sufficient to avoid catastrophic losses.

[3] The Naval Research Laboratory has undertaken a measurement program of the continental shelf and slope waters off the Gulf Coast (Figure 1). The shelf gently slopes from the coast to the shelf break at a depth near 100 m, where the continental slope begins and depths rapidly drop deeper than 3,000 m. Fourteen acoustic Doppler current profilers (ADCPs) were deployed, 6 along the outer continental shelf in 2 lines consisting of 3 moorings each at depths of 60 m (M1, M2, and M3, Line 1) and 90 m (M4, M5, and M6, Line 2) that measured currents with 2 m vertical resolution every 15 minutes, and 8 along the continental slope at depths of 500 and 1000 m that will not be discussed further here. Absolute near-bottom pressure and near-bottom temperature were also measured. The horizontal spacing between instruments was about 15 km. Hurricane Ivan's eye and region of maximum wind stress passed directly over these moorings (Figure 2).

[4] The oceanic response over the outer shelf to Ivan can be separated into 4 stages determined by the magnitude and direction of the wind stress. Stage 1 occurred when the front half of the storm generated downwelling favorable wind conditions [*Pedlosky*, 1979]. Stage 2 occurred when the radius of maximum winds (also called the eyewall), which was about 40 km for Ivan (Figure 2), crossed the outer shelf. Stage 3 occurred when the rear half of the storm outside the eyewall crossed the outer shelf, and Stage 4, or the "relaxation stage" [*Price et al.*, 1994], a predominantly baroclinic response, occurred after the hurricane had passed. Detailed observations of the oceanic response (moorings 1–6, Figure 1) to Stages 1 through 3 are the focus here.

2. Instrumentation and Data Processing

[5] The 6 moored instrument packages on the shelf consisted of 300 kHz RD Instruments Workhorse ADCPs and Sea-Bird Electronics Model 26 wave/tide gauges protected in trawl-resistant bottom mounts commonly known as Barnys [*Teague et al.*, 2002]. The ADCPs rested about 0.5 m above the ocean bottom and measured current profiles with 2 m vertical resolution and 1 cm s^{-1} accuracy, and near-bottom temperature.

[6] Removal of measurement error and high frequency motions, not of interest here, was accomplished by applying a 6th order low-pass Butterworth filter with a 4-hour cut-off frequency forwards and backward to eliminate phase shifts. After filtering, the K_1, O_1, M_2, N_2, and S_2 tidal constituents were computed using the tidal analysis program T_TIDE [*Pawlowicz et al.*, 2002] and then removed.

3. Observation Analysis

[7] The response to Stage 1 at all 6 moorings was onshore advection in the upper water column and offshore advection in the lower water column generated by coastal downwelling (Figure 3) [*Keen and Glenn*, 1994]. Ivan moved across the Gulf of Mexico with a mean translation speed near 6.3 m s^{-1}, suggesting Stage 1 should last about 15 hours. An estimate of favorable downwelling/upwelling conditions can be calculated as the running integral of alongshore wind stress over time, $\tau(t)$, with downwelling/upwelling favorable conditions present when $\tau(t)$ is monotonically decreasing/increasing [*Yankovsky and Garvine*, 1998]. Several days before Ivan's influence was felt $\tau(t)$ (not shown) displayed a linear decrease accompanied by a linear increase in near bottom temperature at all 6 moorings, suggesting downwelling was occurring prior to Stage 1. On September 15 at 0800 UTC (15 hours prior to eyewall arrival), $\tau(t)$ became more negative while temperatures rose, indicating the rate of downwelling increased during Stage 1. The 15 hours of enhanced downwelling resulted in near bottom temperatures rising about 3°C at all 6 moorings.

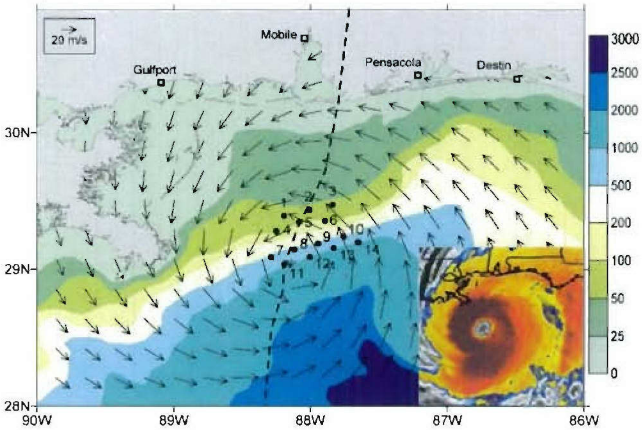

Figure 1. Bathymetry, instrument locations, hurricane path, and wind speed in the northeastern Gulf of Mexico. Solid circles labeled 1–14 show the locations of 14 ADCPs deployed along the shelf and slope. The thick dashed line is the path of Hurricane Ivan, which moved to the north. Arrows show the direction and magnitude of the wind speed when Ivan was over the moorings. The inset is a colorized infrared picture taken by the NOAA GOES-12 satellite highlighting the storm's size and well-delineated eye wall.

[8] The current structure during Stage 1 (Figures 4a–4d) suggests frictionally dominated flow in which the surface and bottom Ekman layers overlap [*Keen and Glenn*, 1994; *Shen and Evans*, 2001]. Theory shows Ekman veering is reduced and surface Ekman layer velocities closely align with wind stress as the ratio of water depth to Ekman depth decreases [*Neumann and Pierson*, 1966]. During Stage 1, surface velocities were more closely aligned to wind stress at Line 1 than at Line 2 and showed minimal veering with depth in the surface and bottom Ekman layers, consistent with theory. The overlapping Ekman layers suggest flow over the outer shelf is not geostrophically balanced. Thus, the surface depression and nearly instantaneous geostrophic adjustment [*Price et al.*, 1994] normally associated with hurricane passage may not occur inshore of the shelf break.

[9] The response to Stage 2 began around 2300 UTC on September 15 (Figures 2, 3, and 4e–4g), lasted about 7 hours, and included a rapidly deepening surface Ekman layer that extended nearly to the bottom. Ekman layer thickness depends on friction velocity [*Zikanov et al.*, 2003], which in turn depends on the magnitude of stress applied at each boundary. Bottom and surface stresses are typically calculated using quadratic stress laws that strongly depend on near-bottom velocity and surface wind stress, respectively. The wind stress [*Large and Pond*, 1981; *Donelan et al.*, 2004] increased monotonically until the eyewall passed over the outer shelf and then decreased (Figures 2 and 4a–4g). In response, surface velocities increased and the Ekman layer thickened as the eyewall approached, driving strong near-bottom velocities that veered off-shelf in the thin bottom Ekman layer (Figures 3 and 4a–4d). This continued until the surface wind stress, which reached an order of magnitude greater than the bottom stress (10 Pa to 1 Pa), caused the surface Ekman layer to dominate the full water column along Line 1 and to extend nearly to the bottom along Line 2 (Figures 4e–4f). Full penetration of the surface Ekman layer along Line 1 took about 4 hours, during which the near bottom velocities veered off-shelf and near bottom temperatures rose about 4°C (Figure 3). Sea surface temperatures over the array prior to the storm were between 28 and 29°C, and the near-bottom temperatures along Line 1 peaked at 27.9, 27.4, and 26.7°C. This strongly suggests horizontal advection and vertical mixing both contributed to the rapid temperature increase, and that the water column became nearly homogeneous. Once the surface Ekman layer extended to the bottom, near-bottom velocities turned along-shelf and aligned with the wind stress. The flow then became nearly barotropic.

[10] Throughout Stage 2 the bottom Ekman layer along Line 2 veered off-shelf, likely due to deeper water, and near-bottom temperatures increased, peaking at 26.1, 26.1, and 22.7°C. Contrary to line 1, the across-shelf currents at M4 and M5 remained strongly baroclinic with off-shelf near-bottom flow throughout Stage 2 (Figure 3), suggesting horizontal advection was the dominant mechanism for the

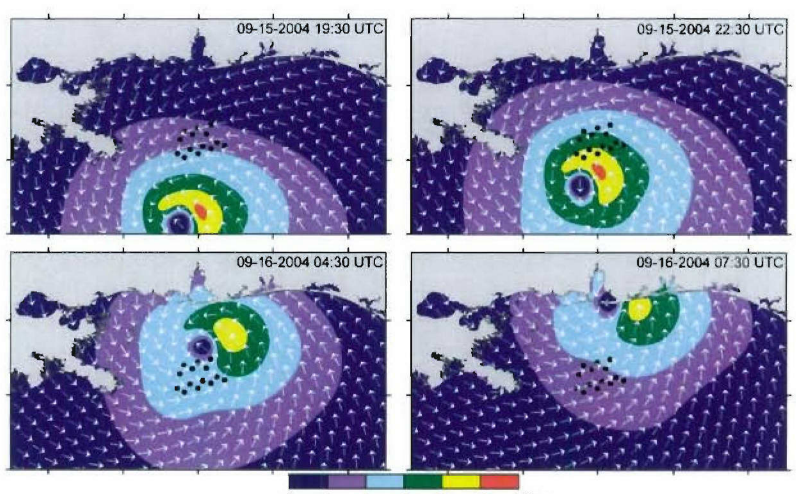

Figure 2. Hurricane Ivan's wind stress field as it approached the Gulf Coast. Contour intervals are 2 Pa. Black dots show mooring locations and arrows depict the wind stress direction.

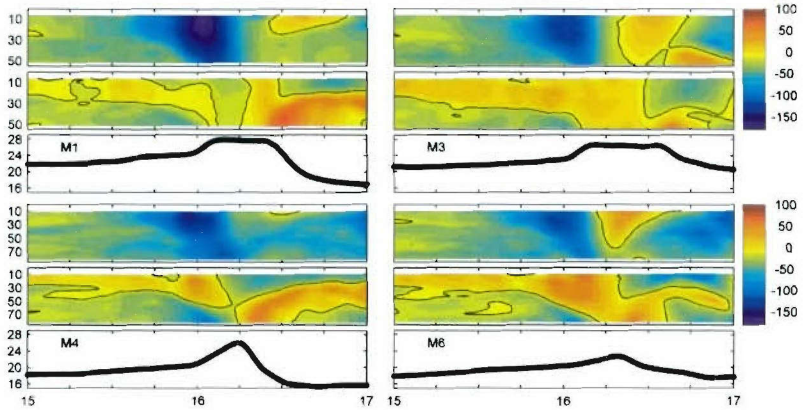

Figure 3. (top) Along- and (middle) across-shelf velocity contours (left axes are depth in meters, and colorbar units are cm s^{-1}). Contour intervals are 10 cm s^{-1}, and the black contour represents 0 cm s^{-1}. (bottom) Bottom temperatures (left axes in °C) at moorings 1, 3, 4, and 6 from Sep 15 to Sep 17.

temperature increase at these 2 moorings. The bottom currents at M6 turned on-shelf prior to the temperature reaching its peak, and the temperature at M3 remained relatively constant after peaking for a longer duration than at M1 and M2, even after the bottom velocity turned on-shelf (Figure 3). This indicates that vertical mixing at M3 and M6, where the wind stress was greatest, maintained the temperature at M3 and continued increasing the temperature at M6, despite onshore flow of cooler waters from off-shelf.

[11] Transport per unit width along both lines was biased towards the left of the storm track, with peak transports of 70, 65, and 53 m^2 s^{-1} at M1, M2, and M3, and 79, 74, and 70 m^2 s^{-1} at M4, M5, and M6. A numerical simulation of Hurricane Frederic [*Cooper and Thompson*, 1989], which followed a path similar to Ivan, displayed a rightward bias of transport, but their smoothed bathymetry excluded the "boot" of Louisiana. *Keen et al.* [1994] found regional geometry played a key role in determining flows when regional features matched the scale of the storm, developing coastal cells [*Keen and Slingerland*, 1993]. The coastal geometry and Ivan's wind field were similar in scale, however, the shelf changes from a broad shallow shelf to a narrow steep shelf over a short distance (Figure 1). The geometry is further complicated by a concave coastline and the "boot" of Louisiana. The wind stress (Figure 2) generated by Ivan forced water from a broad region onto

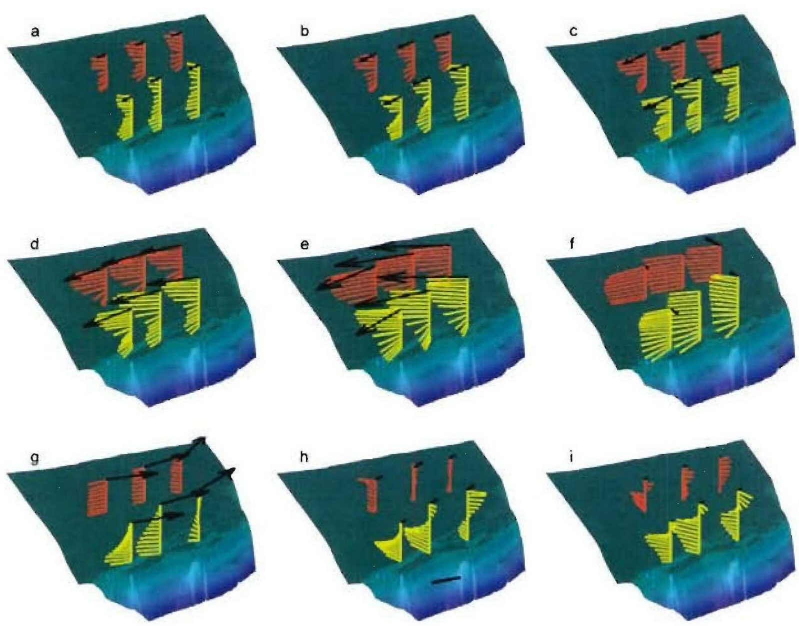

Figure 4. Current and wind stress vectors for moorings 1 through 6 on the outer shelf every three hours beginning on Sep 15, 1200 UTC. Red vectors denote the 60 m line and yellow vectors denote the 90 m line. The black vectors represent the wind stress. (a)–(d) Stage 1, overlapping surface and bottom Ekman layers during continuous upwelling. (e)–(g) Stage 2, surface Ekman layer extends nearly to the bottom during peak wind stress. (h)–(i) Stage 3, after hurricane passage the wind stress significantly decreases, the surface Ekman layer weakens, and the bottom layer rotates clockwise (inertially). The black line on panel h represents a velocity of 100 cm s^{-1} and a wind stress of 4 Pa.

the continental shelf, but the boot forced the outflow to pass through a narrow region. Thus, a modified coastal cell likely developed with accelerated flow between the eye and the boot [e.g., *Forristall*, 1980, Figure12], generating larger transports left of the eye. The effect of the boot on hurricane generated flows has also been noted by *Keen and Allen* [2000] and *Keen and Glenn* [1995, 1999].

[12] The dominant response during Stage 3 was near-bottom onshore flows accompanied by near-bottom temperature decreases. The strongest response left of the eye (Figures 3 and 4h–4i) was a consequence of the wind stress rotating in opposite directions at different rates and magnitudes left and right of the eye during Stages 2 and 3 (Figures 2 and 4). The wind stress rotated counter-clockwise about 180° in 6 hours at M1, M2, M4, and M5. The winds rotated faster than the currents, ultimately opposing and slowing them (Figure 4g). As Stage 3 progressed, the wind stress decreased and the surface Ekman layer thinned, but the bottom currents continued unabated and rotated clockwise, driving a strong onshore flow that decreased temperatures 11°C in 6 hours. In contrast, the wind stress rotated clockwise about 180° in 12 hours at M3 and M6, with the currents rotating slightly slower (Figures 4e–4g). The wind stress was stronger because the eye did not pass directly over M3 and M6 (Figures 1, 2, and 4f). Hence, the surface Ekman layer remained thicker and the currents nearly aligned along-shelf to the east, except in the thin bottom layer which still flowed weakly onshore. The wind stress then steadily decreased, the surface layer thinned, and the bottom layer thickened. However, the near-bottom currents were weaker than at the other 4 moorings; thus, temperatures only decreased 6°C in 6 hours. Upwelling favorable flow after hurricane landfall was seen for Hurricane Andrew [*Keen and Glenn*, 1999]. However, it seems unlikely the onshore flow near the bottom associated with Ivan was wind induced, because near-bottom onshore flow was rapidly established, offshore flow near the surface had not yet been established, and upwelling favorable wind stress was rapidly diminishing after the storm made landfall.

4. Summary

[13] The oceanic response over the outer continental shelf during the passage of Hurricane Ivan was observed in unprecedented detail. The response proceeded through three distinct stages in response to the wind field. During the first stage, a downwelling regime in which the surface and bottom Ekman layers overlap, all 6 moorings responded similarly with a 3°C temperature increase. The responses to the second and third stages were complex, with significantly different responses left and right of the eye, and at 60 and 90 m water depths, even though the moorings were separated by less than 15 km. The complexity of the response stems from many sources, including different magnitudes and rotation directions of the wind stress left and right of the eye, hydrographic conditions, enhanced vertical mixing right of the eye, and local geometry (coastline and bottom slope). The boot of Louisiana significantly narrows the width of the shelf in its proximity (Figure 1) and likely accelerated the currents over the shelf and enhanced transports left of the eye.

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